

Lepton Mixing Matrix Element U_{13} and New Assignments of Universal Texture for Quark and Lepton Mass Matrices

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Abstract

We reanalyze the mass matrix model of quarks and leptons that gives a unified description of quark and lepton mass matrices with the same texture form. By investigating possible types of assignment for the texture components of the lepton mass matrix, we find that a different assignment for neutrinos than for charged leptons can also lead to consistent values of the MNSP lepton mixing matrix. We also find that the predicted value for the lepton mixing matrix element U_{13} of the model depends on the assignment. A proper assignment will be discriminated by future experimental data for U_{13} .

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Recent neutrino oscillation experiments[1] have highly suggested a nearly bi-maximal lepton mixing ($\sin^2 2\theta_{12} \sim 1$, $\sin^2 2\theta_{23} \simeq 1$) in contrast with the small quark mixing. In order to reproduce these lepton and quark mixings, mass matrices of various structures with texture zeros have been investigated in the literature[2]-[4]. Recently a mass matrix model based on a discrete symmetry Z_3 and a flavor $2 \leftrightarrow 3$ symmetry has been proposed[5] with following universal structure for all quarks and leptons

$$P^\dagger \begin{pmatrix} 0 & A & A \\ A & B & C \\ A & C & B \end{pmatrix} P^\dagger, \quad (1)$$

where P is a diagonal phase factor. It was pointed out[5] that this structure leads to reasonable values of the Cabibbo–Kobayashi–Maskawa (CKM) [6] quark mixing as well as lepton mixing. An assignment (we refer it as Type A) for the texture components with $A = \pm\sqrt{\frac{m_2 m_1}{2}}$, $B = \frac{1}{2}(m_3 + m_2 - m_1)$, and $C = -\frac{1}{2}(m_3 - m_2 + m_1)$ with the i -th generation mass m_i has been proposed both for up and down quarks in Ref.[5]. Unfortunately, the type A assignment leads to a somewhat small predicted value for the CKM quark mixing matrix element $|V_{ub}| = 0.0020 - 0.0029$ with respect to the present experimental value $|V_{ub}| = 0.0036 \pm 0.0007$ [7]. Subsequently, it has been pointed out[8] that there exist other possible new assignments for texture components and that the combination of the new assignment (we refer it Type B) with $A = \pm\sqrt{\frac{m_3 m_1}{2}}$, $B = \frac{1}{2}(m_3 + m_2 - m_1)$, and $C = \frac{1}{2}(m_3 - m_2 - m_1)$ for up quarks, and the previously proposed type A assignment for down quarks is phenomenologically favorable for reproducing the consistent values of CKM quark mixing. By taking the type A assignment both for neutrinos and charged leptons, the authors in Ref. [5] have obtained the consistent values for the lepton mixing matrix of the model with the present experimental data. In the present paper, stimulated by the success in the quark sector, we discuss the neutrino masses and lepton mixings of the model with use of the new assignments for charged leptons and neutrinos.

Our mass matrices M_u , M_d , M_ν , and M_e for up quarks (u, c, t), down quarks (d, s, b), neutrinos (ν_e, ν_μ, ν_τ) and charged leptons (e, μ, τ), respectively are given as follows[5]:

$$M_f = P_f^\dagger \widehat{M}_f P_f^\dagger, \quad (2)$$

with

$$\widehat{M}_f = \begin{pmatrix} 0 & A_f & A_f \\ A_f & B_f & C_f \\ A_f & C_f & B_f \end{pmatrix} \quad (f = u, d, \nu, e), \quad (3)$$

where P_f is the diagonal phase matrix and A_f , B_f , and C_f are real parameters.

Hereafter, for brevity, we will omit the flavor index. The eigenmasses of Eq. (3) are given by $\frac{1}{2} [B + C - \sqrt{8A^2 + (B + C)^2}]$, $\frac{1}{2} [B + C + \sqrt{8A^2 + (B + C)^2}]$, and $B - C$. Therefore, there are three types of assignments for the texture components of \widehat{M} according to the assignments for the eigenmass m_i .

(i) Type A:

$$-m_1 = \frac{1}{2} [B + C - \sqrt{8A^2 + (B + C)^2}], \quad (4)$$

$$m_2 = \frac{1}{2} [B + C + \sqrt{8A^2 + (B + C)^2}], \quad (5)$$

$$m_3 = B - C. \quad (6)$$

This is the case for which $B - C$ has the largest value. In this type, the texture components of \widehat{M} are expressed in terms of m_i as

$$A = \pm \sqrt{\frac{m_2 m_1}{2}}, \quad B = \frac{1}{2} (m_3 + m_2 - m_1), \quad C = -\frac{1}{2} (m_3 - m_2 + m_1). \quad (7)$$

The orthogonal matrix O that diagonalizes \widehat{M} [$(O^T \widehat{M} O = \text{diag}(-m_1, m_2, m_3))$] is given by

$$O \equiv \begin{pmatrix} c & \pm s & 0 \\ \mp \frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \mp \frac{s}{\sqrt{2}} & \frac{c}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}. \quad (8)$$

Here c and s are defined by $c = \sqrt{\frac{m_2}{m_2 + m_1}}$ and $s = \sqrt{\frac{m_1}{m_2 + m_1}}$. Note that the elements of O are independent of m_3 . This type A assignment is proposed in Ref.[5].

(ii) Type B: This assignment is obtained by exchanging m_2 and m_3 in type A:

$$-m_1 = \frac{1}{2} [B + C - \sqrt{8A^2 + (B + C)^2}], \quad (9)$$

$$m_2 = B - C, \quad (10)$$

$$m_3 = \frac{1}{2} [B + C + \sqrt{8A^2 + (B + C)^2}]. \quad (11)$$

In this type, the texture components of \widehat{M} are expressed as

$$A = \pm \sqrt{\frac{m_3 m_1}{2}}, \quad B = \frac{1}{2} (m_3 + m_2 - m_1), \quad C = \frac{1}{2} (m_3 - m_2 - m_1). \quad (12)$$

The orthogonal matrix O' that diagonalizes \widehat{M} [$(O'^T \widehat{M} O' = \text{diag}(-m_1, m_2, m_3))$] is given by

$$O' \equiv \begin{pmatrix} c' & 0 & \pm s' \\ \mp \frac{s'}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{c'}{\sqrt{2}} \\ \mp \frac{s'}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{c'}{\sqrt{2}} \end{pmatrix}. \quad (13)$$

Here c' and s' are defined by $c' = \sqrt{\frac{m_3}{m_3+m_1}}$ and $s' = \sqrt{\frac{m_1}{m_3+m_1}}$.

(iii) Type C: This assignment is obtained by exchanging m_1 for m_2 in type B. However, This type is not useful in the following discussions.

The type B and type C are new assignments proposed in Ref.[8]. Taking the type B assignment for up quarks and the type A for down quarks, we have obtained consistent values for the CKM quark mixing matrix in Ref.[8]. Stimulated by the above new assignment, Koide[9] has proposed a new universal texture of quark and lepton mass matrices which is an extension of our model with an extended flavor $2 \leftrightarrow 3$ symmetry.

Now let us discuss the lepton mixing matrix of the model. In our model, M_ν and M_e have the same zero texture with same or different assignments as follows:

$$M_\nu = P_\nu^\dagger \begin{pmatrix} 0 & A_\nu & A_\nu \\ A_\nu & B_\nu & C_\nu \\ A_\nu & C_\nu & B_\nu \end{pmatrix} P_\nu, \quad (14)$$

$$M_e = P_e^\dagger \begin{pmatrix} 0 & A_e & A_e \\ A_e & B_e & C_e \\ A_e & C_e & B_e \end{pmatrix} P_e, \quad (15)$$

where P_ν and P_e are the CP -violating phase factors. We find that the assignments that are consistent with the present experimental data are following two cases:

Case(i): Type A assignment both for neutrinos and charged leptons are taken.

Case(ii): Type B assignment for neutrinos and type A for charged leptons are taken.

The other possible cases fail to reproduce consistent lepton mixing. Since the case(i) was discussed in Ref.[5], let us discuss the case(ii) in this paper. In case(ii), $M_f = P_f^\dagger \widehat{M}_f P_f$ ($f = \nu, e$) are diagonalized by the biunitary transformation as $D_f = U_{Lf}^\dagger M_f U_{Rf}$, where $U_{L\nu} \equiv P_\nu^\dagger O_\nu$, $U_{R\nu} \equiv P_\nu O_\nu$, $U_{Le} \equiv P_e^\dagger O'_e$, and $U_{Re} \equiv P_e O'_e$. Here O_ν and O'_e are orthogonal matrices that diagonalize \widehat{M}_ν and \widehat{M}_e , respectively. Thus, we obtain the Maki–Nakagawa–Sakata–

Pontecorv (MNSP) [10] lepton mixing matrix U as follows:

$$U = U_{Le}^\dagger U_{L\nu} = O_e'^T P_e P_\nu^\dagger O_\nu = \begin{pmatrix} c_e' c_\nu + \rho_\nu s_e' s_\nu & c_e' s_\nu - \rho_\nu s_e' c_\nu & -\sigma_\nu s_e' \\ -\sigma_\nu s_\nu & \sigma_\nu c_\nu & \rho_\nu \\ s_e' c_\nu - \rho_\nu c_e' s_\nu & s_e' s_\nu + \rho_\nu c_e' c_\nu & \sigma_\nu c_e' \end{pmatrix}, \quad (16)$$

where ρ_ν and σ_ν are defined by

$$\rho_\nu = \frac{1}{2}(e^{i\delta_{\nu 3}} + e^{i\delta_{\nu 2}}) = \cos \frac{\delta_{\nu 3} - \delta_{\nu 2}}{2} \exp \left[i \left(\frac{\delta_{\nu 3} + \delta_{\nu 2}}{2} \right) \right], \quad (17)$$

$$\sigma_\nu = \frac{1}{2}(e^{i\delta_{\nu 3}} - e^{i\delta_{\nu 2}}) = \sin \frac{\delta_{\nu 3} - \delta_{\nu 2}}{2} \exp \left[i \left(\frac{\delta_{\nu 3} + \delta_{\nu 2}}{2} + \frac{\pi}{2} \right) \right]. \quad (18)$$

Here we have set $P \equiv P_e P_\nu^\dagger \equiv \text{diag}(e^{i\delta_{\nu 1}}, e^{i\delta_{\nu 2}}, e^{i\delta_{\nu 3}})$, and we have taken $\delta_{\nu 1} = 0$ without loss of generality. Then, the explicit magnitudes of the components of U are expressed as

$$|U_{11}| \simeq \sqrt{\frac{m_2}{m_2 + m_1}}, \quad |U_{12}| \simeq \sqrt{\frac{m_1}{m_2 + m_1}}, \quad |U_{13}| = \sqrt{\frac{m_e}{m_\tau + m_e}} \sin \frac{\delta_{\nu 3} - \delta_{\nu 2}}{2}, \quad (19)$$

$$|U_{22}| = \sqrt{\frac{m_2}{m_2 + m_1}} \sin \frac{\delta_{\nu 3} - \delta_{\nu 2}}{2}, \quad |U_{23}| = \cos \frac{\delta_{\nu 3} - \delta_{\nu 2}}{2}, \quad |U_{33}| \simeq \sin \frac{\delta_{\nu 3} - \delta_{\nu 2}}{2}. \quad (20)$$

Therefore, we obtain

$$\tan^2 \theta_{\text{solar}} = \frac{|U_{12}|^2}{|U_{11}|^2} \simeq \frac{m_1}{m_2}, \quad (21)$$

$$\sin^2 2\theta_{\text{atm}} = 4|U_{23}|^2 |U_{33}|^2 \simeq \sin^2(\delta_{\nu 3} - \delta_{\nu 2}), \quad (22)$$

$$|U_{13}|^2 \simeq \frac{m_e}{m_\tau} \sin^2 \frac{\delta_{\nu 3} - \delta_{\nu 2}}{2}. \quad (23)$$

Note that $|U_{ij}|$ are almost independent of $(\delta_{\nu 3} + \delta_{\nu 2})$. Therefore, the independent parameters in $|U_{ij}|$ are $\theta_e' = \tan^{-1}(m_e/m_\tau)$, $\theta_\nu = \tan^{-1}(m_1/m_2)$, and $(\delta_{\nu 3} - \delta_{\nu 2})$. Since θ_e' is already fixed by the charged lepton masses, θ_ν and $(\delta_{\nu 3} - \delta_{\nu 2})$ are adjustable parameters in our model.

Let us estimate the values of θ_ν and $(\delta_{\nu 3} - \delta_{\nu 2})$ by fitting the experimental data. In the following discussions we consider the normal mass hierarchy $\Delta m_{23}^2 = m_3^2 - m_2^2 > 0$ for the neutrino mass. In this situation, we can ignore the evolution effects. They only give small correction effects enough to be neglected. Generally speaking, we must consider the renormalization group equation (RGE) effect when the neutrino masses have the inverse hierarchy or almost degenerate ($m_1 \simeq m_2$). However, these scenarios are denied from (21)

and (26). Hence, the neutrino masses must have the normal mass hierarchy and we do not need to consider the RGE effects.

When we use the expressions (19)-(23) at the weak scale, the parameters $\delta_{\nu 2}$ and $\delta_{\nu 3}$ do not mean the phases that are evolved from those at the unification scale. Hereafter, we use the parameters $\delta_{\nu 2}$ and $\delta_{\nu 3}$ as phenomenological parameters that approximately satisfy the relations (19)-(23) at the weak scale.

We have[11]

$$|U_{13}|_{\text{exp}}^2 < 0.054 \quad , \quad (24)$$

from the CHOOZ[12], solar[13], and atmospheric neutrino experiments[1] with 3σ range. From the global analysis of the SNO solar neutrino experiment[11, 13] with 3σ range, we have

$$\Delta m_{12}^2 = m_2^2 - m_1^2 = \Delta m_{\text{sol}}^2 = (5.2 - 9.8) \times 10^{-5} \text{ eV}^2, \quad (25)$$

$$\tan^2 \theta_{12} = \tan^2 \theta_{\text{sol}} = 0.29 - 0.64 \quad , \quad (26)$$

for the large mixing angle (LMA) MSW solution. From the atmospheric neutrino experiment[1, 11], we also have

$$\Delta m_{23}^2 = m_3^2 - m_2^2 \simeq \Delta m_{\text{atm}}^2 = (1.4 - 3.4) \times 10^{-3} \text{ eV}^2, \quad (27)$$

$$\tan^2 \theta_{23} \simeq \tan^2 \theta_{\text{atm}} = 0.49 - 2.2 \quad , \quad (28)$$

with 3σ range. The observed fact $\tan^2 \theta_{\text{atm}} \simeq 1.0$ highly suggests $\delta_{\nu 3} - \delta_{\nu 2} \simeq \pi/2$. Hereafter, for simplicity, we take

$$\delta_{\nu 3} - \delta_{\nu 2} = \frac{\pi}{2} \quad . \quad (29)$$

Under this constraint, the model predicts

$$|U_{13}|^2 = \frac{1}{2} \frac{m_e}{m_\tau + m_e} = 0.00014 \quad , \quad \text{or} \quad \sin^2 2\theta_{13} = 0.00055 \quad . \quad (30)$$

Here we have used the running charged lepton mass at $\mu = \Lambda_X$ [14]: $m_e(\Lambda_X) = 0.325 \text{ MeV}$, $m_\mu(\Lambda_X) = 68.6 \text{ MeV}$, and $m_\tau(\Lambda_X) = 1171.4 \pm 0.2 \text{ MeV}$. The value in Eq.(30) is consistent with the present experimental constraints Eq.(24) and can be checked in neutrino factories in future [15] which have sensitivity for $\sin^2 2\theta_{13}$ as $\sin^2 2\theta_{13} \geq 10^{-5}$.

From the mixing angle θ_{sol} in the present model, we obtain

$$\frac{m_1}{m_2} \simeq \tan^2 \theta_{\text{sol}} = 0.29 - 0.64. \quad (31)$$

Then, we obtain the neutrino masses

$$\begin{aligned}
m_1^2 &= (0.48 - 6.8) \times 10^{-5} \text{ eV}^2 , \\
m_2^2 &= (5.7 - 16.6) \times 10^{-5} \text{ eV}^2 , \\
m_3^2 &= (1.4 - 3.4) \times 10^{-3} \text{ eV}^2 .
\end{aligned} \tag{32}$$

Next let us discuss the CP-violation phases in the lepton mixing matrix. The Majorana neutrino fields do not have the freedom of rephasing invariance, so that we can use only the rephasing freedom of M_e to transform Eq.(16) to the standard form

$$\begin{aligned}
U_{\text{std}} &= \text{diag}(e^{i\alpha_1^e}, e^{i\alpha_2^e}, e^{i\alpha_3^e}) U \text{diag}(e^{\pm i\pi/2}, 1, 1) \\
&= \begin{pmatrix} c_{\nu 13} c_{\nu 12} & c_{\nu 13} s_{\nu 12} e^{i\beta} & s_{\nu 13} e^{i(\gamma - \delta_\nu)} \\ (-c_{\nu 23} s_{\nu 12} - s_{\nu 23} c_{\nu 23} s_{\nu 13} e^{i\delta_\nu}) e^{-i\beta} & c_{\nu 23} c_{\nu 12} - s_{\nu 23} s_{\nu 12} s_{\nu 13} e^{i\delta_\nu} & s_{\nu 23} c_{\nu 13} e^{i(\gamma - \beta)} \\ (s_{\nu 23} s_{\nu 12} - c_{\nu 23} c_{\nu 12} s_{\nu 13} e^{i\delta_\nu}) e^{-i\gamma} & (-s_{\nu 23} c_{\nu 12} - c_{\nu 23} s_{\nu 12} s_{\nu 13} e^{i\delta_\nu}) e^{-i(\gamma - \beta)} & c_{\nu 23} c_{\nu 13} \end{pmatrix} \tag{33}
\end{aligned}$$

Here, α_i^e comes from the rephasing in the charged lepton fields to make the choice of phase convention, and the specific phase $\zeta \equiv \pm\pi/2$ is added on the right-hand side of U in order to change the neutrino eigenmass m_1 to a positive quantity. The CP-violating phase δ_ν , the additional Majorana phase factors β and γ [16, 17] in the representation Eq.(33) are calculable and obtained as

$$\begin{aligned}
\delta_\nu &= \arg \left[\frac{U_{12} U_{22}^*}{U_{13} U_{23}^*} + \frac{|U_{12}|^2}{1 - |U_{13}|^2} \right] \simeq \arg \left(\frac{U_{12} U_{22}^*}{U_{13} U_{23}^*} \right) \\
&\simeq \frac{\pi}{2} \pm \frac{\pi}{2} - \frac{\delta_{\nu 3} + \delta_{\nu 2}}{2}, \text{ (for } A_e = \pm |A_e|) \\
\beta &= \arg \left(\frac{U_{12}}{U_{11}} \right) + \zeta \simeq \frac{\pi}{2} \mp \frac{\pi}{2} + \zeta, \text{ (for } A_\nu = \pm |A_\nu|) \\
\gamma &= \arg \left(\frac{U_{13}}{U_{11}} \right) + \zeta \simeq -\frac{\pi}{2} + \zeta,
\end{aligned} \tag{34}$$

by using the relation $m_e \ll m_\tau$. Note that the sign ambiguity in A_e and A_ν can be absorbed into the phases $\delta_{\nu 2}$ and $\delta_{\nu 3}$ by the simultaneous redefinition of them. Hence, we can also predict the averaged neutrino mass $\langle m_\nu \rangle$ which appears in the neutrinoless double beta decay[17] as follows:

$$\begin{aligned}
\langle m_\nu \rangle &\equiv \left| -m_1 U_{11}^2 + m_2 U_{12}^2 + m_3 U_{13}^2 \right| \\
&\simeq \left| \frac{2m_1 m_2}{m_1 + m_2} - m_3 \frac{m_e}{2m_\tau} e^{i(\delta_{\nu 3} + \delta_{\nu 2})} \right| \\
&\simeq \frac{2m_1 m_2}{m_1 + m_2} \simeq 0.0017 - 0.0050 \text{ eV} .
\end{aligned} \tag{35}$$

Let us compare the result of the case (ii) with the case (i). In case (i), we have[5]

$$|U_{13}|^2 \simeq \frac{m_e}{m_\mu} \sin^2 \frac{\delta_{\nu 3} - \delta_{\nu 2}}{2}, \quad (36)$$

while the result of $\tan^2 \theta_{\text{solar}}$ and $\sin^2 2\theta_{\text{atm}}$ are the same as Eqs. (21) and (22), respectively. Consequently, the values of θ_ν and $(\delta_{\nu 3} - \delta_{\nu 2})$ and the prediction for the neutrino masses of the model are also the same both for the cases (i) and (ii). However, an interesting difference between the cases (i) and (ii) appears in the prediction for $|U_{13}|^2$. Namely the value of $|U_{13}|^2$ in the case (ii) are much smaller than in the case (i) as seen in Eqs.(23) and (36). Therefore, the cases (i) and (ii) are distinguishable by the experimental determination of $|U_{13}|^2$ in future, although they are both allowed from the present experimental data.

In conclusion, we have reanalyzed the lepton mixing matrix using the mass matrix model of Ref.[5] with the universal texture form. We have shown that the case (ii) with the type A assignment for \widehat{M}_e and the type B for \widehat{M}_ν can also lead to consistent values for the lepton mixing matrix. The neutrino masses, CP-violating phases, and the averaged neutrino mass $\langle m_\nu \rangle$ in the case (ii) are predicted. It is also shown that the predicted value for $|U_{13}|$ depends on the assignment for the texture components of the mass matrices. Therefore, a proper assignment will be discriminated by future experimental data for $|U_{13}|$.

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